RADAR INVESTIGATIONS OF EUROPA, GANYMEDE, AND CALLISTO

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The radar echoes from Europa, Ganymede, and Callisto are extraordinary. It has been known for 15 years that these objects' radar reflectivities dwarf values reported for comets, the Moon, the inner planets, and nonmetallic asteroids. When the radar transmission is circularly polarized, the icy satellites return echoes with the incident handedness preserved, in contrast with the behavior of other targets. At the principal Arecibo wavelength of 13 cm, the circular polarization ratio μ_C, of echo power in the same sense of circular polarization as transmitted (the SC sense) to that in the opposite (OC) sense, is about 1.5, 1.4, and 1.2 for Europa, Ganymede and Callisto, but is only ~0.1 for the Moon and less than 0.4 for most other planetary radar targets. The linear polarization ratio (μ_L = OL/SL) is about one half for all three satellites, again considerably larger than for other targets. The satellites' 13-cm radar albedos increase from Callisto to Ganymede to Europa, whose OC radar reflectivity is the same as that of a metal sphere. The satellites' albedo distributions overlap. The most prominent radar features are tentatively identified with Galileo Regio and the Valhalla basin. Wavelength dependence in μ_C and albedo is negligible from 3.5 to 13 cm and, at least for μ_C, possibly through 70 cm. Evidence for μ_C features is lacking, except for indications of a weak hemispheric asymmetry for Callisto.

Ostro *et al.* (1) summarized the history of radar observations of the satellites, reported results of Arecibo/Goldstone observations during 1987-91, and reviewed efforts to understand the electromagnetic scattering process responsible for the unusual echoes. The icy satellites' echoes are due not to external surface reflections but to volume scattering from within the regoliths. The high radar transparency of ice compared with that of silicates permits deeper radar sounding, longer photon path lengths, and higher-order scattering from regolith heterogeneities (2); radar is seeing Europa, Ganymede, and Callisto in a manner that the Moon has never been seen. As suggested by Hapke (3), the satellites' radar behavior apparently involves the coherent backscatter effect (4-9). Intersatellite and intrasatellite fractional variations in albedo greatly exceed variations in μ_C; this is consistent with predictions of coherent backscatter theory and implies that albedo might be a crude indicator of relative silicate abundance.

There are similarities between the icy Galilean satellites' radar properties and those of the radar-bright polar caps on Mars and Mercury. Most recently, Rignot *et al.* (10) have reported airborne radar images of the percolation zone in the Greenland ice sheet that reveal icy terrain with radar properties similar to those of the icy Galilean satellites. However, the detailed subsurface configuration in the Greenland zone, where heterogeneities are the product of seasonal melting and refreezing, are unlikely to resemble those on the satellites. Hence, a variety of natural subsurface configurations apparently can yield exotic radar signatures. Still, the Greenland percolation zone constitutes a uniquely accessible, natural laboratory for studying relations between subsurface configurations and unusual radar scattering processes.

Radar observations of the satellites have just begun to produce dynamically useful results. Estimates of 1987-91 echo Doppler frequencies showed Callisto to be lagging its ephemeris by an average of 200 ± 50 km. Arecibo 1992 observations of Ganymede and Callisto (11) yielded the first successful radar ranging measurements to the satellites. Both objects showed roundtrip time-delay residuals of order 1 msec relative to predictions based on the E-3 ephemeris. Errors in the predicted along-track positions (orbital phases) can account for most of the residuals: Ganymede led its ephemeris by 122 km and Callisto lagged its ephemeris by 307 km, with uncertainties of order 10 km. The results of these pilot experiments suggest that radar ranging with upgraded telescopes could be useful for long-term monitoring of satellite orbits.

Echoes obtainable with the upgraded Arecibo will be nearly twenty times stronger than any obtained so far. The next Jupiter opposition within the Arecibo declination window occurs in 1999. Meanwhile, bistatic radar imaging with Goldstone and the Very Large Array should be attempted (to refine estimates of radar features' source regions) and monostatic Goldstone ranging experiments should be conducted on all three satellites.

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